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RESEARCH MEMORANDUM

A STUDY OF THE RADIATION FROM LAMINAR AND TURBULENT OPEN PROPANE-AIR FLAMES AS A FUNCTION OF FLAME AREA, EQUIVALENCE RATIO, AND FUEL FLOW RATE

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON

August 24, 1954

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SUMMARY

Radiation measurements have been made on open propane-air flames to find the extent to which radiant flux intensity can be used to measure the surface area of such flames. For laminar flames of a given equivalence ratio, intensity changes linearly with both fuel flow rate and photographically measured surface area. Moreover, the intensity per unit area of the flame depends on only the equivalence ratio.

Turbulent flame intensity is also proportional to fuel flow rate. Laminar and turbulent flames at identical conditions of flow rate, equivalence ratio, and burner diameter have approximately the same radiation intensities. Furthermore, the spectral intensity distributions appear to be the same for both types of flames, which suggests that the kinetics may also be the same. These results are entirely compatible with the current "extended surface" concept of turbulent flame structure; they do not, however, rule out other theories of the structure of turbulent flames.

INTRODUCTION

Much of the theoretical and experimental work on hydrocarbon flames has revolved around the concept of a fundamental burning velocity. This burning velocity or "flame speed" is defined as the rate of advance of a reaction zone into a nonturbulent gas stream. In most practical combustion systems such as furnaces, combustion chambers, and aircraft power plants, however, the burning gases are highly turbulent. The need thus arises for a study of the burning velocities of flames in turbulent gas mixtures.

One common way of expressing the fundamental burning velocity of a laminar flame is as the quotient of the gas volume flow divided by the flame surface area. This ratio would be a convenient method for indicating the fundamental burning velocity in turbulent gas mixtures except that "surface areas" in such systems are difficult to measure. Not only are the reaction zones in rapid and continuous motion, but no certainty exists that the reaction zone or "flame surface" in the turbulent case is identical to that in the laminar one. Even with laminar flames, which have been generally accepted as standards, the burning velocity apparently varies along the surface of an open flame. The simple ratio mentioned therefore indicates only an average burning velocity for laminar flames.

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Attempts have been made to calculate average burning velocities of conical turbulent flames burning on tubes. In analogy to the sharp outline of a laminar flame image in a photographic negative, a locus of maximum intensity was drawn through the photographic image of a turbulent flame brush (fig. 1). As in the case of the laminar flame, the average surface area of the turbulent flame was determined by calculating the area of the surface of revolution of this maximum intensity outline (refs. 1 and 2). When this method is used, burning velocities in turbulent gas mixtures appear to be appreciably higher than those in laminar gas mixtures having the same composition.

Several explanations have been put forth to explain this apparent difference in burning velocity. These can be grouped into chemical and physical mechanisms. The chemical explanations assume that influences such as changes in diffusion rates, transport properties, and temperature distributions have altered the basic kinetics of the reaction and thus reaction zone thickness and burning velocity (ref. 3). The physical explanations assume that whereas the reaction zone may be either a homogeneous sheet or a heterogeneous mixture containing islands of flame, the reaction kinetics have not changed. They postulate that the turbulent gas flow has wrinkled and folded the flame into a more compact form. The surface is assumed to have been extended just enough to allow all the gas flow to pass through some portion of the reaction zone at the proper laminar burning velocity (refs. 4, 5, 6).

Any valid method of measuring burning velocity in the turbulent gas streams must not only measure the surface area of the flame but must also determine whether the flame surface is identical both physically and chemically to that of an equivalent laminar flame. Photographs of some simply distorted flames in turbulent gas streams have been measured and analyzed to determine their surface areas (ref. 5), but such a method is not feasible on the brush flames that usually occur in turbulent gas streams.

The experimentation described in this paper represents an attempt to utilize the light coming from a flame to determine the surface area of the flame. Relative intensity measurements of the total light flux radiated by the flame in different regions of the visible spectrum were used as an index of the volume of the radiating reaction zone and thus "surface" area. Distribution of radiation throughout the flame spectrum was studied as a clue to the similarity of the chemistry of combustion in both laminar and turbulent gas streams.

Propane-air flames having equivalence ratios ranging from 0.9 to 1.3 were examined at Reynolds numbers up to 7000 and average flow velocities up to 65 feet per second. Turbulent burning velocities calculated by both the average surface method and the surface radiation method under consideration are compared. The extent of external air intermixing in turbulent flames is also indicated.

GEOMETRIC ASPECTS OF MEASURING LIGHT FLUX FROM CLOUDS OF RADIATION SOURCES

When a radiation detector is moved away from a point source of light, the light flux impinging on the detector will decrease according to the inverse square law. If a point source of light is increased to a finite size and the distance from the source to the detector is made great in comparison with the dimensions of the source, the inverse square law still holds to a very close approximation (fig. 2). The source may be of any shape so long as its maximum dimension is small compared with the distance between the source and the detector. When this situation exists, appreciable changes can be made in either the intensity per unit surface area or the total surface area of the source, and a nominally linear relation will exist between each of these variables and the intensity of flux registered by the detector located at a constant distance from the source. Let a detector be placed at some relatively large distance from a small spherical homogeneous cloud of nonabsorbing emitters. This cloud is concentric to and completely contained within the sphere of diameter d in figure 2, which defines the limit of permitted error in the inverse square relation. As the radius of the cloud is changed while both the number of emitters per unit volume and their individual strengths remain the same, the radiation intensity at the detector will change linearly with the volume of the cloud. On the other hand, if the cloud size is fixed and either the number of emitters per unit volume or the individual emitter strengths are changed, the detector will then register directly the relative radiation intensities per unit volume of the cloud. These statements will hold true for a nonabsorbing cloud of emitters of any arbitrary size or shape, so long as it remains within the bounds of the limiting sphere of diameter d.

The reaction zone of a laminar flame approximates closely the requirements for the hypothetical cloud of emitters under discussion. The emitters in the flame are largely the diatomic molecules OH, CH, CO, and C_2. The visible spectrum contains mostly CH, CO, and C_2, and a disperse cloud of such emitters does not reabsorb appreciably (ref. 7). Although the distribution of emitters varies through the reaction zone, the luminous sheet of the flame appears homogeneous at a distance, expecially if nonfocused radiant flux is measured. Therefore, the luminous inner cone of a laminar open flame can be thought of as a homogeneous nonabsorbing constant-thickness sheet of radiating particles. In this case the flame surface area is a direct measure of the change in volume of the reaction zone. Fuel flow rate at constant equivalence ratio is also a measure of the size (i.e., the volume) of the reaction zone.

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APPARATUS AND PROCEDURE

Apparatus

Figure 3 is a diagram of the apparatus used in this investigation. The basic elements are the two burner tubes, the photomultiplier detector unit, with a microammeter to register its output, and a fixed focus box camera for taking direct photographs of the flames. A mirror was placed as indicated, 24 inches above the burner lip, to turn the radiation 90° and direct it to the photomultiplier unit. The distance from the mirror to the photomultiplier tube was 49 inches. This arrangement satisfied two of the primary requirements for applying the principles discussed in the previous section. First, by observing the flame from directly above the burner, the source size was kept as constant as possible. Second, the distance between the flame and the detector was kept large enough that the flame could be considered a point source of radiation.

The camera was mounted to take direct photographs of the flames from a direction perpendicular to the axis of the flame. A water-cooled metal burner of 0.536 centimeter inner diameter, equipped with an annular pilot for holding flames at high gas flow rates, was used to generate the turbulent flames. To obtain a wide range of laminar flames for calibration purposes a larger water-cooled unpiloted metal burner of 1.024 centimeter inner diameter was used. These burners were mounted 2.5 inches apart at the same fixed distance from the photomultiplier tube and also equidistant from the vertical plane through the geometric center of its photosensitive surface. At low flow rates flames were laminar on both burners so that the constancy of the laminar flame characteristics could be checked on both tubes. C.p. grade propane was used in all the experiments, and the fuel and air were metered by calibrated rotameters.

Intensity measurements were taken at two specific regions of the spectrum by using either a yellow or a blue filter in front of the photomultiplier tube. Figure 4 shows a comparison of the propane-air flame spectra with the transmission characteristics of the two filters and the photomultiplier tube sensitivity. The yellow filter transmits mainly the C_2 radiation from the flame, whereas the blue one allows radiations from CO, CH, and other emitters as well as some from C_2 to pass.

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Procedure

Intensity measurements. - Measurements were made on a series of laminar and turbulent flames ranging in equivalence ratio from 0.9 to 1.3 and in total flow rate from 120 to 440 cubic centimeters per second. Whenever possible, identical composition and total flow rate conditions were used to generate and measure a laminar flame on the large burner and a turbulent flame on the small, piloted burner. At low flow rates laminar flames of the same composition and flow rate were measured on both burners. Each flame was measured using the blue and the yellow filters in turn in front of the photomultiplier unit. Three readings were made for each measurement. During the measurement of the laminar flames it was found that the ratio of intensities using the two filters depended only on the equivalence ratio of the flame and not on the gas flow rate or burner size, so that this ratio could be used to check the gas metering system.

Photographic measurement of flame surface areas. - Simultaneously with intensity data, direct photographs were taken of all the laminar flames and many of the turbulent flames. Areas of the laminar flames were calculated from these photographs by using a modification of the method described in reference 8. A similar procedure was used to calculate average surface areas of the turbulent flames according to the ideas expressed in references 2 and 3. The details of these calculations are presented in the appendix, where a discussion of the experimental error of this work will also be found.

RESULTS

Laminar Flame Intensity Measurements at Different Flow Rates and Equivalence Ratios

Figures 5 and 6 show that linear relations exist between intensity and both fuel flow rate and flame surface area for laminar propane-air flames up to equivalence ratios of 1.3. Equivalence ratios of 1.4 and 1.5 showed the same linear intensity relation with fuel flow, but the flames were too unsteady and lacking in tip intensity to be photographed for the purpose of making surface area measurements of the flames.

These experimental data for laminar flames on the 1.024 centimeter diameter tube were limited by the blow-off and flash-back of the flame at equivalence ratios less than 1.0 and low flows. At high total flows and richer equivalence ratios, the data were limited by the occurrence of flame unsteadiness, flame turbulence, or flames too long for the experimental error size limit imposed by the equipment. Thus the data represent the total range of data obtainable on the 1.024 centimeter diameter tube with propane-air mixtures at atmospheric pressure. Within these limits the experimental data are compatible with the principles of radiation measurement expressed previously. These data are tabulated in table I.

The photomultiplier unit picks up a small amount of carbon monoxide radiation from the outer mantle of a flame. Although this radiation may be a significant part of that passed by the blue filter, a smaller amount is passed by the yellow filter. The fraction of the total radiation due to the mantle has not been determined experimentally. In interpreting the linear behavior of the intensity curves of both the yellow and the blue filters, the effect of the radiation from the outer mantle was neglected.

Filter Intensity-Ratio Method of Measuring Equivalence Ratio of Laminar Flames

The comparison of filter intensity curves in either figures 5(a) and (b) or 6(a) and (b) indicates that the straight lines for a single equivalence ratio have a different slope for the yellow and the blue filters. When the ratio of the yellow and the blue filter intensity data is plotted against equivalence ratio, the curve shown in figure 7 is obtained. The ratio is independent of flow velocity within the range shown in the curves. The filter ratio is therefore an indication of the equivalence ratio of the flame.

The curve appears to level off from an equivalence ratio of 1.3 to 1.4 as shown. In addition to the effects of flame temperature and mixture composition, this leveling-off might be due to the fact that the richer flames mix with the surrounding air and actually burn at equivalence ratios of approximately 1.3 even though the flames are laminar. Burning velocity measurements on such rich flames should be an index of whether they are burning at the initial premixed equivalence ratio or at some leaner equivalence ratio caused by secondary air entrainment. Such flames are too unsteady to be measured by the usual methods, however, and some procedure such as the use of the radiant flux method under discussion must be utilized.

Surface Intensity Variations in Laminar Propane-Air Open Flames

Lean propane-air Bunsen flames appear to have a conical envelope of uniform intensity. As the flames increase in richness above an equivalence ratio of 1.0, however, the intensity begins to diminish from the base to the tip of the cone, and the tip thus appears to fade. At equivalence ratios of 1.2 and higher, the flames become less steady and greater portions of the tip fade away. In spite of this tip fading, the relation of intensity to fuel flow and surface area remains linear for the higher equivalence ratios, as shown in figures 5 and 6. This linearity may be accounted for by assuming that even though increased gas flow lengthens the flame, the proportional surface intensity distribution remains constant for a given equivalence ratio.

When intensity per unit surface area is calculated, it is found to depend on only fuel-air ratio and not on total gas flow rate. The variation of the unit area intensity with equivalence ratio does show the effect of the fading, as indicated by the drop-off in the yellow and blue filter curves in figure 8. The difference in the shape of the curves is probably due to the different radiations passed by the two filters. The yellow filter passes mainly C_2 radiation and thus shows an approximately linear relation until tip fading decreases its over-all average intensity per unit surface area. The blue filter passes CH, HCO, and CO radiation as well as C_2 radiation; thus there is the interaction of variations of intensity with equivalence ratio for each emitter, as well as decreased intensities per unit area caused by tip fading. Tip fading, unstable flames that could not be satisfactorily photographed, and the cut-off at equivalence ratios of 1.3 for the yellow-blue filter ratio all combined to indicate that the experimental data beyond equivalence ratios of 1.3 would be less reliable.

When intensity measurements were made on laminar flames seated on the 0.536 centimeter diameter tube, an anomalous tube effect was discovered in that the intensity readings for this tube were less than the values for exactly corresponding flames on the 1.024 centimeter tube. Check measurements made under all experimental conditions of fuel flow and equivalence ratio revealed that intensity values on the small tube were about 14 percent less than the corresponding values on the large tube, and that the difference was constant in all cases. A few experiments were performed with glass burner tubes having inner diameters of 0.577, 0.795, and 1.125 centimeters, and some typical results of these experiments are compared with the data from the metal burners in figure 9. The "tube effect" decreases in magnitude with increasing diameter and there is an indication that it disappears above a diameter of 1 centimeter. The intensity variation was not caused by light absorption for different path lengths of hot gas, for this possibility was checked by examining flames from the side as well as from above. No change in the intensity difference was observed. Neither was the intensity decrease caused by a decrease in the flame surface area, inasmuch as photographs of laminar flames for identical conditions on both tubes showed identical flame surface areas. At the present time no satisfactory explanation can be given for this "tube effect." Experimental work has shown that the ratio of corresponding intensities between any two tubes is a constant, so that intensity data on two different tubes can be compared directly by using the proper correction factor. In view of what has been said, the intensity data shown in figure 8 are plotted for comparison with data on the 0.536 centimeter diameter tube, although they were taken using the 1.024 centimeter tube. The correction factor which has been applied to the large tube data is 0.862.

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Surface Intensity Measurements for Equivalent Laminar and Turbulent Flames

By a suitable adjustment of the inlet conditions to the small metal burner it was possible to generate either a laminar or a turbulent flame with the same fuel flow and metered equivalence ratio for a limited range of total gas flow rates. Flame intensity measurements on these flames are shown in figure 10. The intensities are approximately the same for corresponding laminar and turbulent flames, with a possible general increase of about 3 percent for the turbulent over the laminar flames. The straight lines in figure 10 are drawn through the laminar data only.

This comparison has been extended in figure 11, wherein the straight lines represent the laminar flame intensity data from large tube measurements shown in figure 5. These data (shown in fig. 11 without data points) have been corrected by the tube factor of 0.862. Thus they are directly compared in figure 11 with the intensity measurements which were taken of turbulent flames on the small burner at flow rates above which no laminar flames were obtainable. In both figures 10 and 11 the turbulent flame intensities are very close to the laminar values at low and intermediate flow rates; they begin to fall away from the extended laminar flame curves at the higher flow rates. The data for turbulent flames are shown in table II.

DISCUSSION

The radiant flux intensity from laminar flames of a given equivalence ratio has been found to change linearly with the size of the reaction zone as measured by either the fuel flow rate or the luminous surface area of the flame. In addition, the radiant flux intensity per unit area of a flame does not depend on the size of the reaction zone but only on the equivalence ratio of the combustible mixture, the variable which has the most important effect on the number of emitters per unit volume and on their individual strengths. Thus it has been demonstrated, within the range of experimental conditions covered, that radiation measurements can be used to determine the areas of laminar flames once a calibration curve has been obtained.

In the comparison of the radiation intensities of equivalent laminar and turbulent flames, almost identical values are obtained from the two types of flame at low and intermediate flow rates. Moreover, the ratio of intensities using the two filters was found to be the same for the laminar and the turbulent flames in all these cases. This is an indication that the over-all distribution of emitters is the same in these equivalent flames, and suggests that the kinetics are also the same. Turbulent flame intensities start to fall off from the extrapolated laminar flame curves at high total flow rates as shown in figures 10 and 11. However, the yellow-to-blue filter intensity ratio for these turbulent flames was also lower than that for the corresponding laminar flames. This variation indicated that the actual burning mixture might be leaner than the premixed value. Such an effect may result from the turbulent gases intermixing with the surrounding air. The more lean burning mixture could account for most of the intensity decrease at the higher gas flow rates. No discontinuity in intensity was apparent as the flames changed from the laminar to the turbulent region. Even though a tube factor for intensity was found and the intensity curves tailed off at high gas flow rates, the constancy of the tube factor for all conditions and the apparent equivalence ratio compensation for intensity tail-off suggested that the initial principles of the radiant flux measurement as postulated for laminar flames also apply to turbulent flames. This validity is apparent in the curves of figures 11(a) and 11(b), where no break or discontinuity appears in the linear portions of the intensity curves as the flames change from the laminar to the turbulent region.

Up to the present time no satisfactory method of measuring the true surface area (assuming that it exists) of a turbulent flame has been developed. The "extended surface" concept of the structure of a turbulent flame implies that the flame does have a definite surface area and assumes the reaction zone thickness to be the same as that of a laminar flame (refs. 4, 5, and 6). The radiation principles already verified for laminar flames can therefore be applied to this type of turbulent flame. Under the assumptions of the "extended surface" idea, the turbulent flame intensity measurements can be used to calculate the true areas of these flames by employing the plots of figure 8 (intensity per unit area against equivalence ratio) as calibration curves. The turbulent flame speeds calculated from these radiation surface areas can then be compared with the data shown in figure 12, which is a plot of laminar flame speed against equivalence ratio for a variety of laminar Reynolds numbers.

The laminar surface areas used to obtain the flame speeds were calculated from flame photographs as described in the appendix. Some variation exists in the data for the large and the small tubes at the higher equivalence ratios, but this variation is at most a 5 percent decrease in propagation velocity for the small tube. The difference may be apparent rather than real, due to some aerodynamic effect in the long thin flames of the small tube, since the lower equivalence ratio flame speeds are the same for both tubes. There should be no appreciable difference in flame speeds measured on 0.500 inch and 0.25 inch tubes (ref. 8). 3276

When the frustrum method is used to calculate the surface areas of turbulent flames as outlined in the appendix, the burning velocities vary with Reynolds number as shown in figure 13. Similar results have been found by others (refs. 1, 2, and 4).

Figure 14 presents the results of calculating turbulent burning velocities using flame surface areas obtained from the radiation intensity measurements as suggested. For the flames at high flow rates the equivalence ratio of the burning mixture was taken as the value indicated by figure 7 on the basis of the observed yellow-to-blue filter intensity ratio. These burning velocities are approximately equal to the corresponding laminar velocities and, moreover, do not depend on Reynolds number (more exactly, gas flow rate).

The present investigation has not found a method of distinguishing among the different concepts of the structure of turbulent flames. If, for example, the small-scale distortions that appear in a turbulent flame front cause local variations in the burning velocity, perhaps as a result of preheating the combustible mixture, the resultant extended flame area would be less than the corresponding laminar flame area. If, on the other hand, as indicated in reference 3 the turbulent flame becomes a "homogeneous" reaction zone in which the chemistry is entangled with the turbulent mixing rate, the manner of interpreting flame radiation intensities is not clear. A study of the effect of gas inlet temperature on the luminosities of laminar flames and of the dilution of the unburned gas by combustion products may aid in resolving these possibilities.

The answer to the question of whether a small surface element of a turbulent flame is chemically and physically the same as that of a corresponding laminar flame will help determine the structure of turbulent flames. The fact that both intensities and filter intensity ratios for several pairs of corresponding flames are equal is the most significant evidence obtained in this work and helps to answer this question in the affirmative. Although this evidence, in addition to the calculations shown in figure 14, lends support to the idea that the two types of flame surface are similar, it does not exclude other concepts of the structure of a turbulent flame; for example, that the reaction zone of this type of flame may be a thickened homogeneous zone. However, it is very unlikely that the different temperatures and concentrations which would result from a thickened homogeneous zone would give rise to the identical spectral distribution of intensity found for the laminar flame. The experimental technique developed in this work may be used to study and compare more exactly the properties of the surfaces of laminar and turbulent flames by employing an optical system to focus locally on regions of both types of flame. One might, in addition, use a monochromator to study the variation of individual emitter distribution over a given flame surface and also the effect of changing inlet gas temperature on this distribution.

SUMMARY OF RESULTS

Radiant flux intensity measurements were made of laminar and turbulent propane-air flames between equivalence ratio limits of 0.9 and 1.3 for Reynolds numbers up to 7000. The following results were obtained using a 1.024 centimeter diameter burner for laminar flames and a 0.536 centimeter diameter burner for both laminar and turbulent flames:

1. At a given equivalence ratio the radiant flux intensity of laminar flames is directly proportional to fuel volume flow rate.

2. At a given equivalence ratio the radiant flux intensity of turbulent flames is directly proportional to fuel volume flow rate.

3. At a given equivalence ratio the radiant flux intensity of laminar flames is directly proportional to the photographically measured surface area of the flame.

4. Laminar and turbulent flames of identical composition, flow rate, and burner diameter have almost the same radiation intensities. There is no discontinuity of the linear intensity curves in passing from the laminar to the turbulent region.

5. These results are obtained when the radiation intensity is measured with either a yellow filter or a blue filter ahead of the radiation detector.

6. The ratio of the radiant flux intensities measured using the yellow and the blue filters appears to depend on only the equivalence ratio for laminar flames. This statement holds true for turbulent flames at low and intermediate flow rates.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, June 23, 1954

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APPENDIX - CALCULATIONS

Measurement of flame surface area. - In the case of the sharply defined laminar flames, an enlarged photograph of the flame was divided into a number of trapezoids, the slant-heights of which were straight line segments of the outer edge of the luminous zone. The surface area of each section of the flame so generated was calculated by considering it to be a frustum of a right circular cone. The tip of the flame was treated as a hemisphere.

The average surface areas of the rapidly fluctuating turbulent flames were calculated by first drawing a grid across an enlarged photograph of the flame. Along each horizontal line across the flame, the points of maximum intensity of the flame zone were visually estimated and marked. These points were then connected by straight lines along the flame perimeter, thus defining its average surface cross section except for the tip, which could then be roughly estimated by constructing an isosceles triangle on the top trapezoid. The average flame area was then calculated as for the laminar flames.

This technique was checked for both a laminar and a turbulent flame in one case by using a densitometer to plot the envelope of maximum brightness in addition to estimating it visually. The two methods gave essentially the same results for the laminar flame and differed by less than 3 percent for the turbulent flame, an agreement that was well within the expected experimental error for this type of measurement.

Experimental error. - The sources of error in the experimental results lie in (a) the gas metering system, (b) the photomultiplier tube, (c) the photographic surface area measurements, and (d) the pilot flame for the turbulent flames. A check on the reproducibility of the intensity measurements for given flow-meter settings was maintained by measuring the intensity of a "standard" laminar flame several times during every period of work. To determine the effect of the small annular pilot on the small tube flame intensities, a given flame was measured with minimum and maximum possible pilot flames. For the latter case, the intensity was never increased more than 3 percent over the value at minimum pilot size. Usually the pilot was kept at an intermediate size to minimize its effect. Several photographic surface area measurements on a given laminar flame showed a deviation from the average of ±3 percent.

The intensity measurements on both the laminar and turbulent flames also gave a deviation from the mean of ±3 percent; this value is thus given as a measure of the precision of all the experimental data reported herein.

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TABLE I. - FLAME SPEED AND RADIATION DATA FOR LAMINAR FLAMES

Experiment	Tube diameter, cm	Metered equivalence ratio, φ	Fuel flow, cu cm/sec	Total flow, cu cm/sec	Flame surface area, sq cm	Flame speed, cm/sec	Flame radiation intensity, μamp		Radiation intensity ratio, Y/B	Average intensity ratio at constant φ
							Yellow filter	Blue filter		
1a	1.024	0.80	3.2	96.2	3.66	26.28	0.15	0.33	0.455	0.455
2a	1.024	0.90	4.6	127.6	3.97	32.14	0.42	0.84	0.500	0.504
3a	1.024	.90	5.5	152.6	5.02	30.40	.49	.97	.505	
4a	1.024	.90	6.4	177.5	5.81	30.55	.56	1.11	.505	
5a	1.024	.90	7.3	202.5	6.73	30.09	.63	1.25	.504	
6a	1.024	1.00	5.1	126.7	3.61	35.10	0.69	1.23	0.561	0.563
7a	1.024	1.00	6.1	151.5	4.31	35.15	.88	1.55	.568	
8a	1.024	1.00	7.1	176.4	5.09	34.66	.98	1.74	.563	
9a	1.024	1.00	7.7	190.6	5.55	34.34	1.02	1.83	.577	
9b	1.024	1.00	7.7	190.6	5.61	33.98	1.01	1.80	.561	
11a	1.024	1.00	8.1	201.2	5.83	34.51	1.10	1.95	.564	
12a	1.024	1.00	9.1	226.1	6.71	33.70	1.24	2.18	.569	
14a	1.024	1.10	5.6	126.4	3.66	34.54	0.98	1.50	0.653	0.652
15a	1.024	1.10	6.7	151.2	4.44	34.05	1.23	1.87	.658	
16a	1.024	1.10	7.8	176.1	5.13	34.33	1.38	2.13	.648	
17a	1.024	1.10	8.9	200.9	5.76	34.88	1.64	2.50	.656	
18a	1.024	1.10	10.0	225.7	6.79	33.24	1.80	2.80	.643	
20a	1.024	1.20	6.1	125.9	4.36	28.88	1.50	1.79	0.838	0.818
21a	1.024	1.20	7.3	150.7	5.31	28.38	1.76	2.16	.815	
22a	1.024	1.20	8.5	175.4	5.96	29.43	2.00	2.50	.800	
23a	1.024	1.20	9.7	200.2	6.83	29.31	2.39	2.90	.824	
24a	1.024	1.20	10.9	225.0	7.65	29.41	2.62	3.22	.814	
27a	1.024	1.30	6.6	125.3	5.84	21.46	1.68	1.67	1.006	1.003
27b	1.024	1.30	6.6	125.3	----	-----	1.72	1.71	1.006	
28a	1.024	1.30	9.9	188.0	9.01	20.89	2.57	2.56	1.004	
28b	1.024	1.30	9.9	188.0	----	-----	2.67	2.68	.996	
38a	0.536	0.90	4.6	127.6	4.09	31.20	0.34	0.69	0.493	
39a	.536	.90	5.5	152.6	4.97	30.70	.42	.84	.500	
40b	.536	1.00	5.1	126.7	3.59	35.29	.57	1.01	.564	
41a	.536	1.00	6.1	151.5	4.44	34.12	.73	1.30	.562	
42a	.536	1.10	5.6	126.4	----	-----	.91	1.37	.664	
43a	.536	1.10	6.7	151.2	4.67	32.38	1.13	1.70	.665	
44a	.536	1.20	6.1	125.9	----	-----	1.33	1.60	.830	
45a	.536	1.20	7.3	150.7	5.48	27.50	1.58	1.95	.810	
47a	.536	1.30	6.6	125.3	----	-----	1.57	1.57	1.000	

TABLE II. - INTENSITY DATA FOR TURBULENT FLAMES

[Burner diameter = 0.536 centimeter]

Experiment	Yellow intensity, μamp	Blue intensity, μamp	Intensity ratio, Y/B	Radiation equivalence ratio, φ	Metered equivalence ratio, φ	Reynolds number	Fuel flow, cu cm/sec	Total flow, cu cm/sec	Photo surface area, sq cm	Area from radiation: Yellow, sq cm, a	Area from radiation: Yellow, sq cm, b	Area from radiation: Blue, sq cm, a	Area from radiation: Blue, sq cm, b	Photo flame speed, cm/sec	Radiation flame speed: Yellow, cm/sec	Radiation flame speed: Blue, cm/sec	Average radiation flame speed, cm/sec
49a	0.51	1.00	0.510	0.91	0.90	2783	6.4	177.5	----	6.00	----	5.92	----	-----	[a]29.58	[a]29.98	29.78
50a	.55	1.08	.509	.91	.90	3000	6.9	191.4	4.83	6.47	----	6.39	----	39.63	[a]29.58	[a]29.95	29.77
52a	.85	1.51	.563	1.00	1.00	2785	7.1	176.4	----	5.18	----	5.21	----	-----	[a]34.05	[a]33.86	33.96
53a	.95	1.67	.569	1.01	1.00	3000	7.7	190.6	4.32	5.79	----	5.76	----	44.12	[a]32.92	[a]33.09	33.01
53b	.91	1.60	.563	1.00	1.00	3000	7.7	190.6	4.24	5.58	----	5.54	----	44.95	[a]34.16	[a]34.40	34.28
54b	0.99	1.73	0.572	1.01	1.00	3177	8.1	201.2	----	6.04	----	5.97	----	-----	[a]33.31	[a]33.70	33.51
55b	1.10	1.93	.570	1.01	1.00	3570	9.1	226.1	----	6.71	----	6.66	----	-----	[a]33.70	[a]33.95	33.83
56b	1.20	2.09	.574	1.01	1.00	4000	10.2	253.3	5.12	7.32	----	7.21	----	49.47	[a]34.60	[a]35.13	34.87
57a	1.24	1.89	.656	1.10	1.10	2785	7.8	176.1	----	5.30	----	5.28	----	-----	[a]33.23	[a]33.35	33.29
58b	1.35	2.05	.659	1.10	1.10	3000	8.4	189.7	4.26	5.77	----	5.73	----	44.53	[a]32.88	[a]33.11	32.99
59a	1.44	2.19	0.658	1.10	1.10	3178	8.9	200.9	----	6.15	----	6.12	----	-----	[a]32.67	[a]32.83	32.75
60a	1.57	2.41	.651	1.10	1.10	3570	10.0	225.7	----	6.71	----	6.73	----	-----	[a]33.64	[a]33.54	33.59
61b	1.75	2.71	.646	1.10	1.10	4000	11.2	252.9	5.05	7.48	----	7.57	----	50.08	[a]33.81	[a]33.41	33.61
62c	1.93	3.08	.626	1.08	1.10	5000	14.0	316.1	6.24	8.25	8.73	8.60	8.80	50.66	[b]36.21	[b]35.92	36.07
63a	2.26	3.64	.621	1.07	1.10	6000	16.8	379.3	7.53	9.66	10.56	10.17	10.52	50.37	[b]35.92	[b]36.06	35.98
64a	1.68	2.11	0.796	1.19	1.20	2787	8.5	175.4	----	5.79	----	5.93	----	-----	[a]30.29	[a]29.58	29.94
65a	1.91	2.39	.800	1.20	1.20	3000	9.1	188.8	4.66	6.62	----	6.74	----	40.52	[a]28.52	[a]28.01	28.26
66a	1.94	2.43	.798	1.19	1.20	3181	9.7	200.2	----	6.89	----	6.83	----	-----	[a]29.93	[a]29.31	29.62
67a	2.29	2.86	.801	1.20	1.20	3576	10.9	225.0	----	7.90	----	8.03	----	-----	[a]28.48	[a]28.02	28.25
68b	2.33	3.08	.756	1.18	1.20	4000	12.2	251.7	----	8.03	8.29	8.65	8.51	-----	[b]30.36	[b]29.58	29.97
69b	2.75	3.73	0.737	1.17	1.20	5000	15.2	314.7	6.25	9.48	9.96	10.48	10.25	50.35	[b]31.60	[b]30.70	31.15
70a	3.20	4.34	.737	1.17	1.20	6000	18.3	377.6	7.22	11.03	11.59	12.19	11.92	52.30	[b]32.58	[b]31.68	32.13
71b	3.60	5.01	.719	1.16	1.20	7000	21.3	440.5	----	12.41	13.33	14.07	13.69	-----	[b]33.05	[b]32.18	32.62
72a	2.32	2.47	.939	1.25	1.30	3000	9.9	188.0	5.31	9.24	8.23	9.88	7.79	35.40	[b]22.84	[b]24.13	23.48
73a	2.76	3.19	.865	1.22	1.30	4000	13.1	250.6	5.69	11.00	9.48	12.76	9.30	44.04	[b]26.43	[b]26.95	26.69
74c	3.52	4.12	0.854	1.22	1.30	5000	16.4	313.3	6.84	14.02	12.10	16.41	12.01	45.80	[b]25.89	[b]26.09	25.99
75a	4.12	4.76	.866	1.22	1.30	6000	19.7	375.9	----	16.41	14.16	19.04	13.88	-----	[b]26.55	[b]27.08	26.82
76a	4.44	5.48	.810	1.20	1.30	7000	23.0	438.6	----	17.69	15.31	21.92	15.39	-----	[b]28.65	[b]28.50	28.58

[a]Calculated using metered φ.
[b]Calculated using radiation φ.

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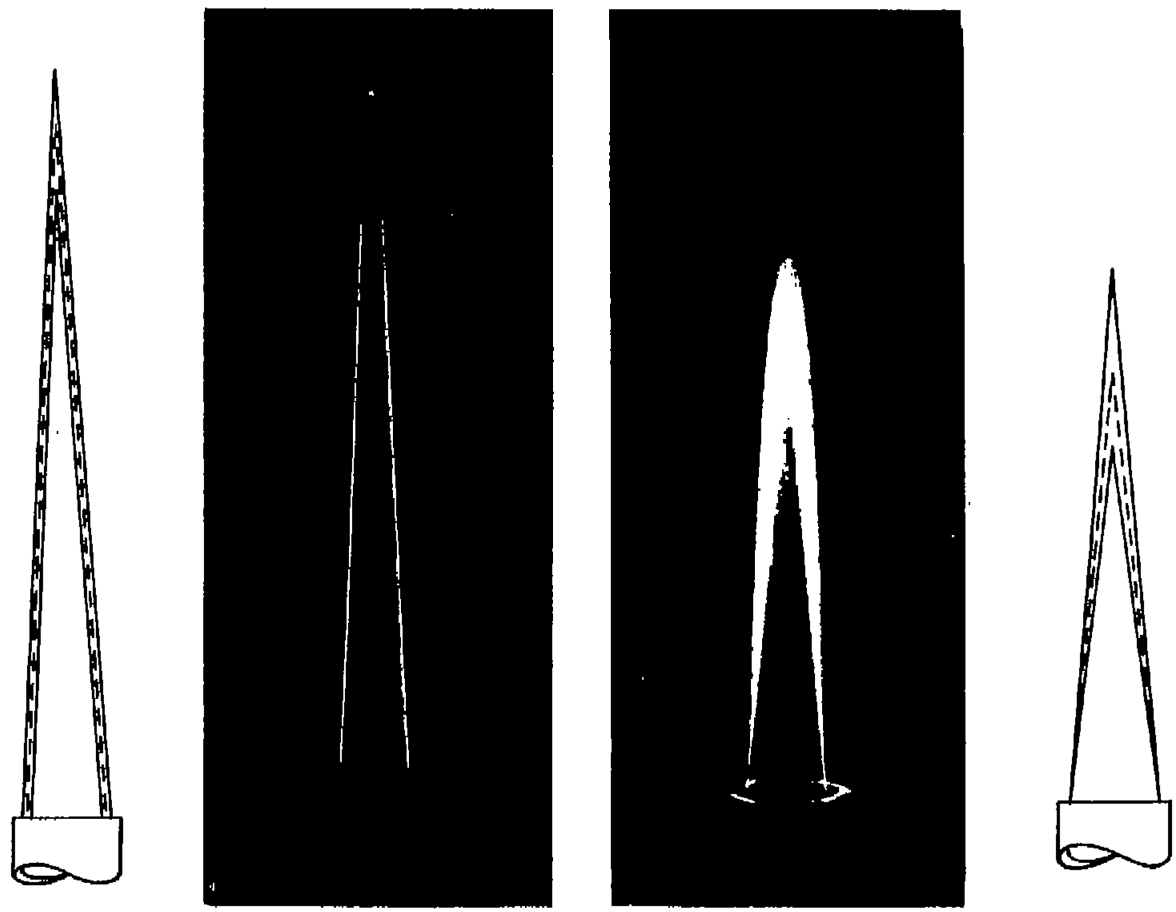


Laminar Turbulent C-36219

Figure 1. - Photographs of laminar and turbulent propane-air flames at same equivalence ratios, flow rates, and tube diameters and drawings indicating points of maximum flame image intensity.

3276

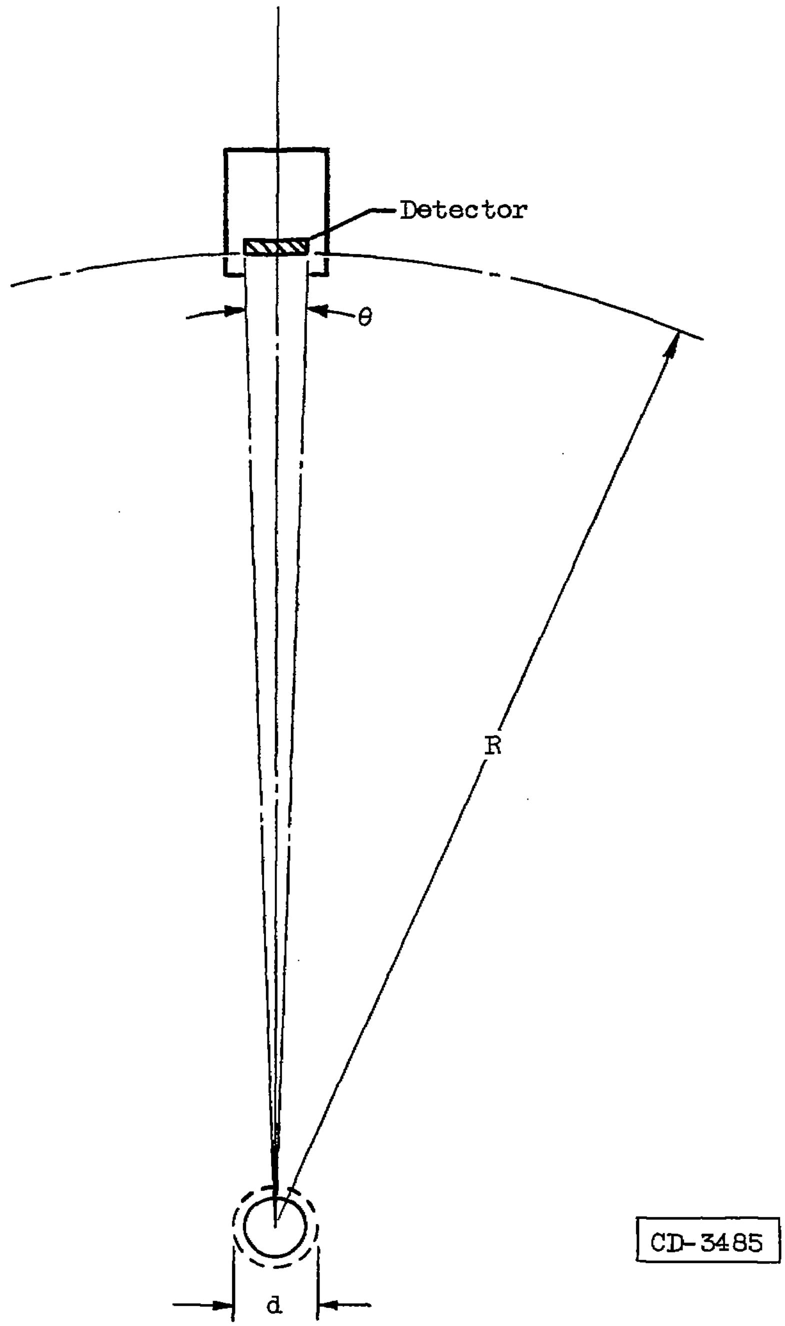


Figure 2. - Diagram illustrating geometric principles of light flux measurement. Conditions: $R >> d$; θ small enough that $\theta \approx \tan \theta$.

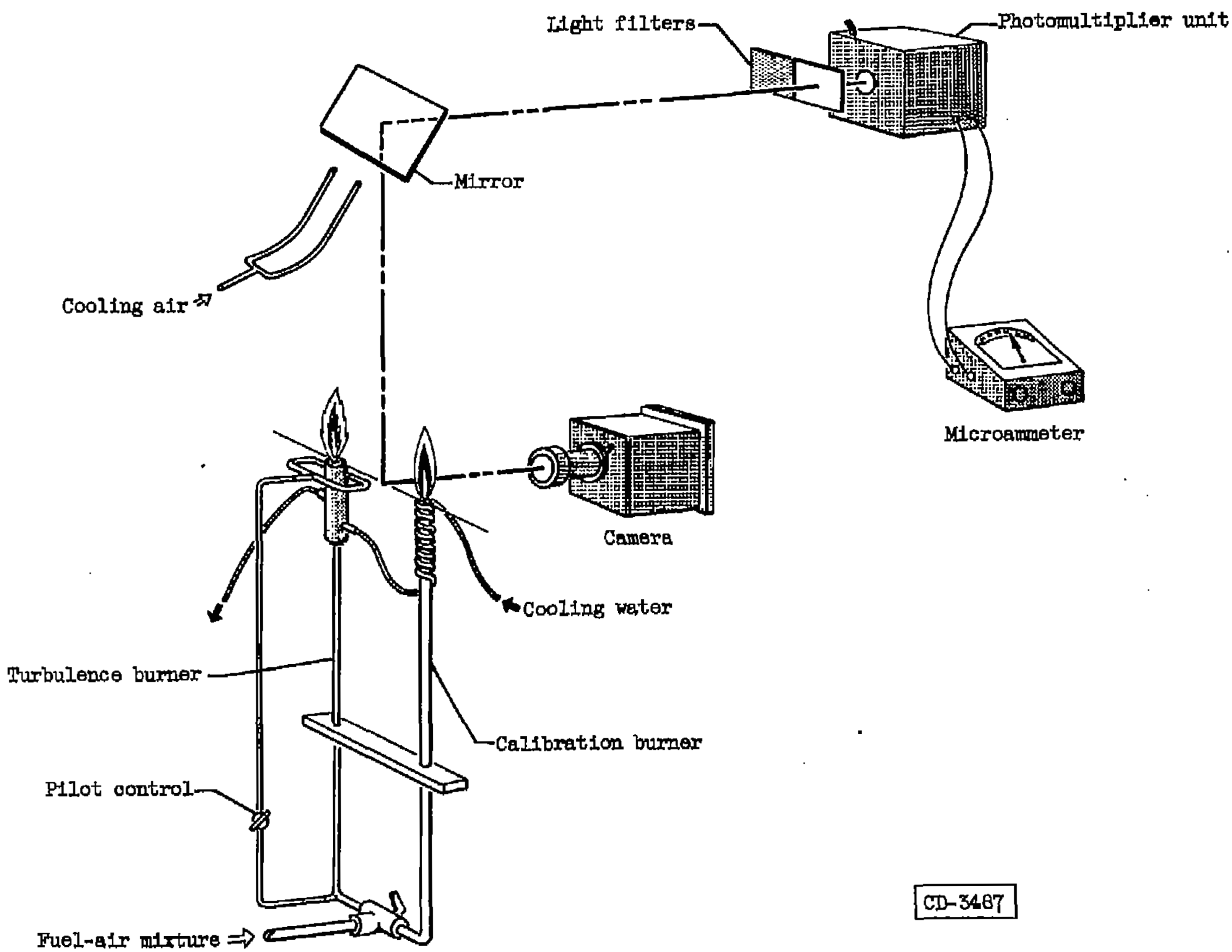


Figure 3. - Diagram of apparatus for determining surface areas of flames.

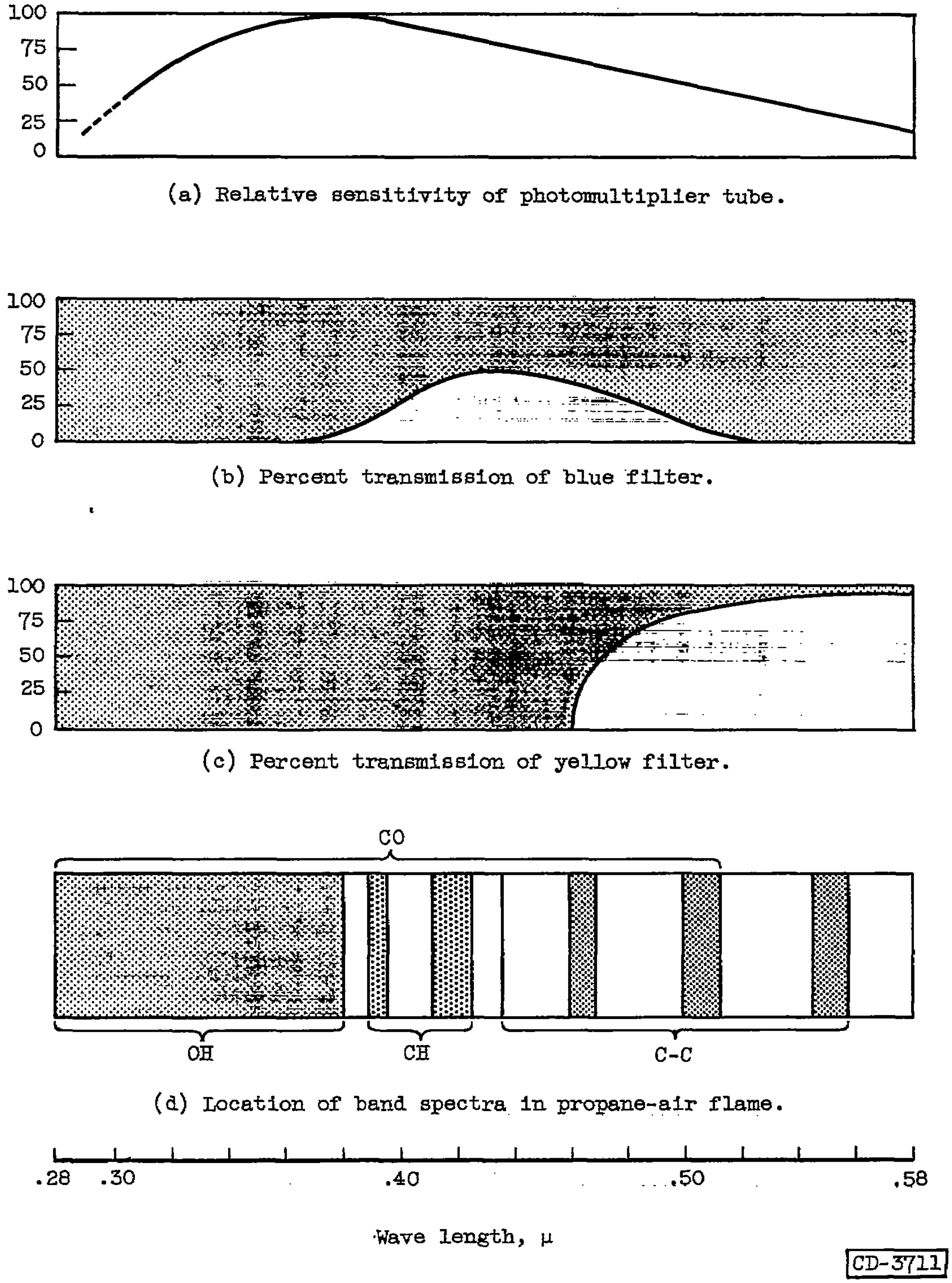
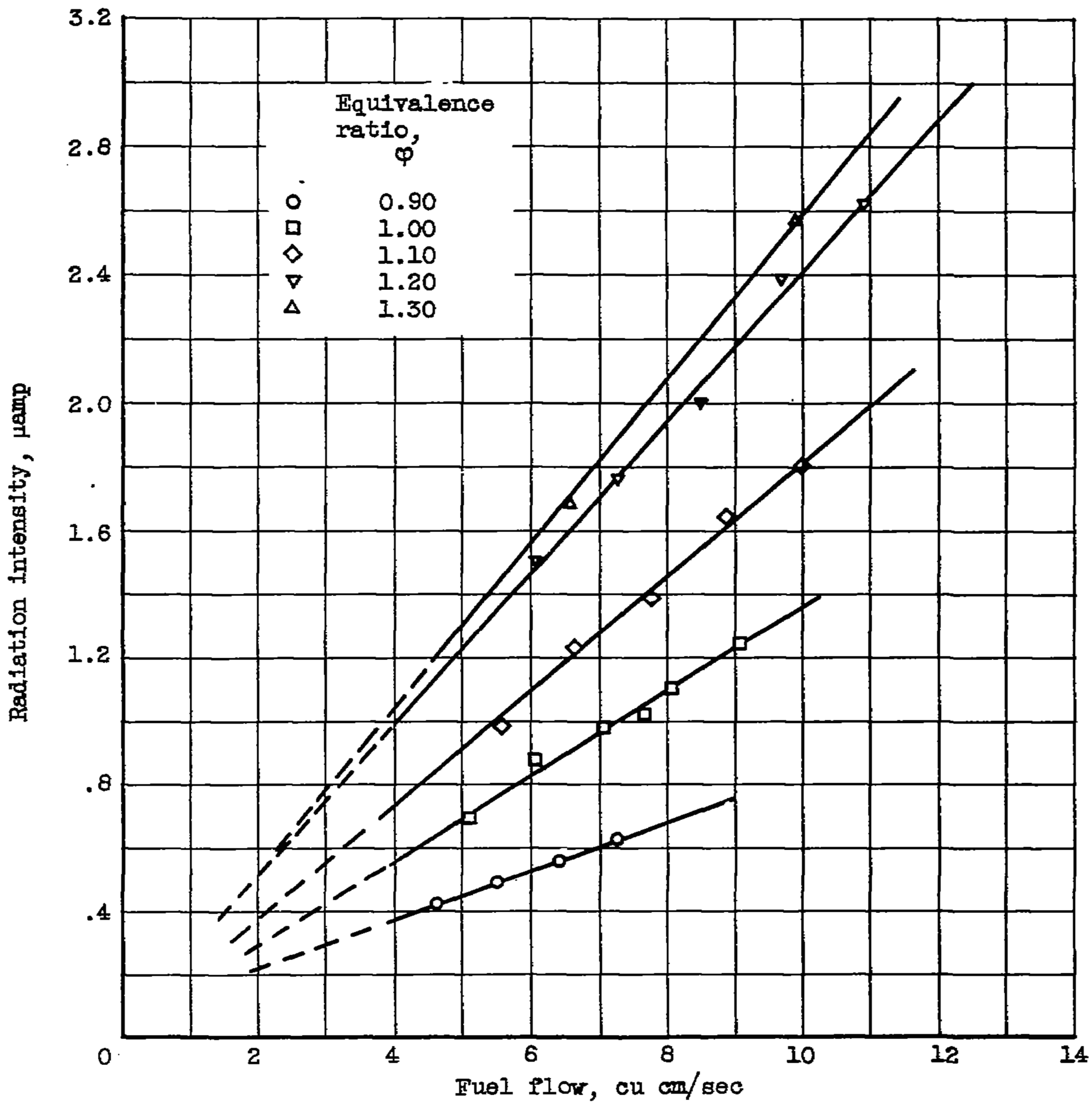


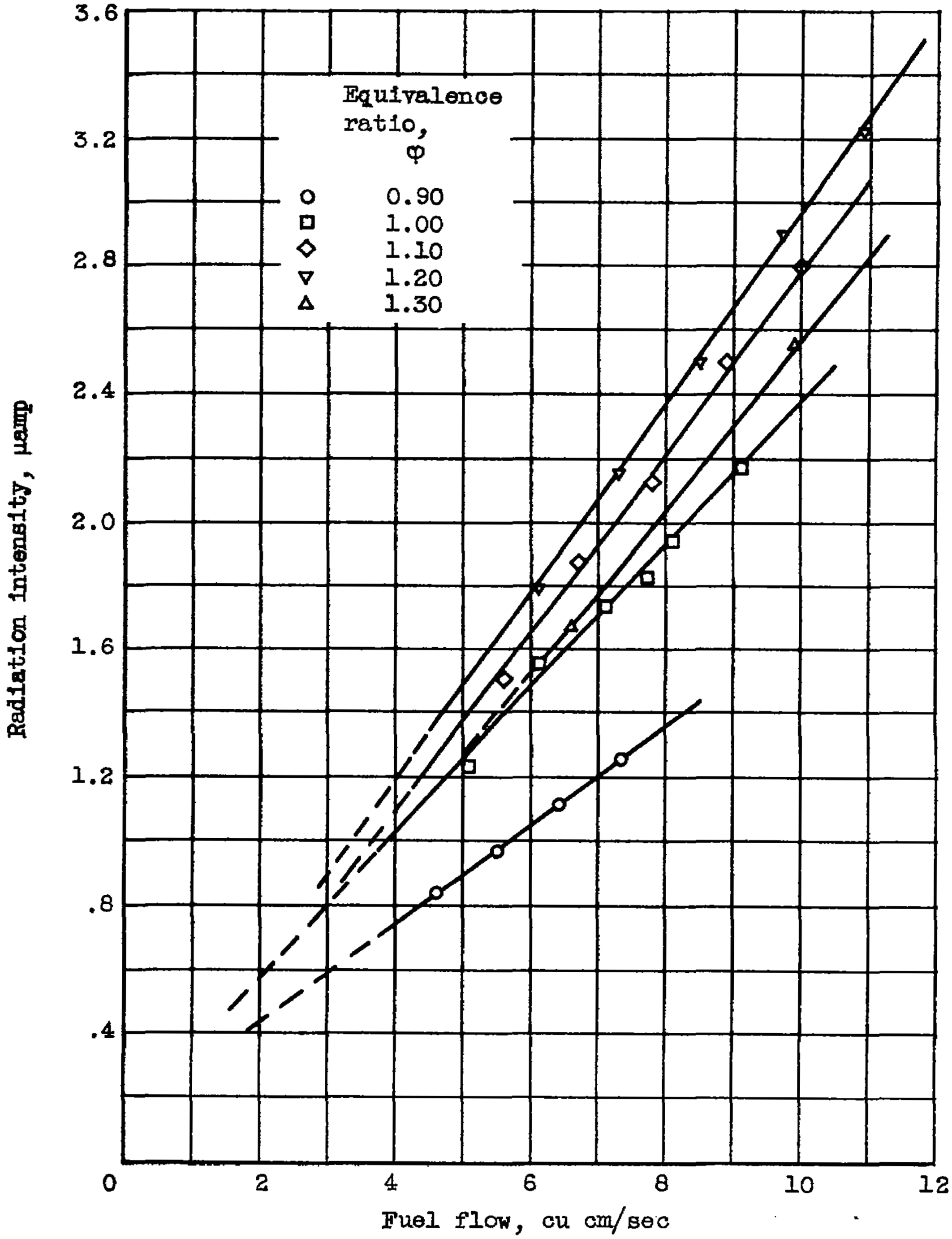
Figure 4. - Optical properties of photomultiplier tube, filters, and propane-air flames used in radiant flux measurements.



(a) Yellow filter.

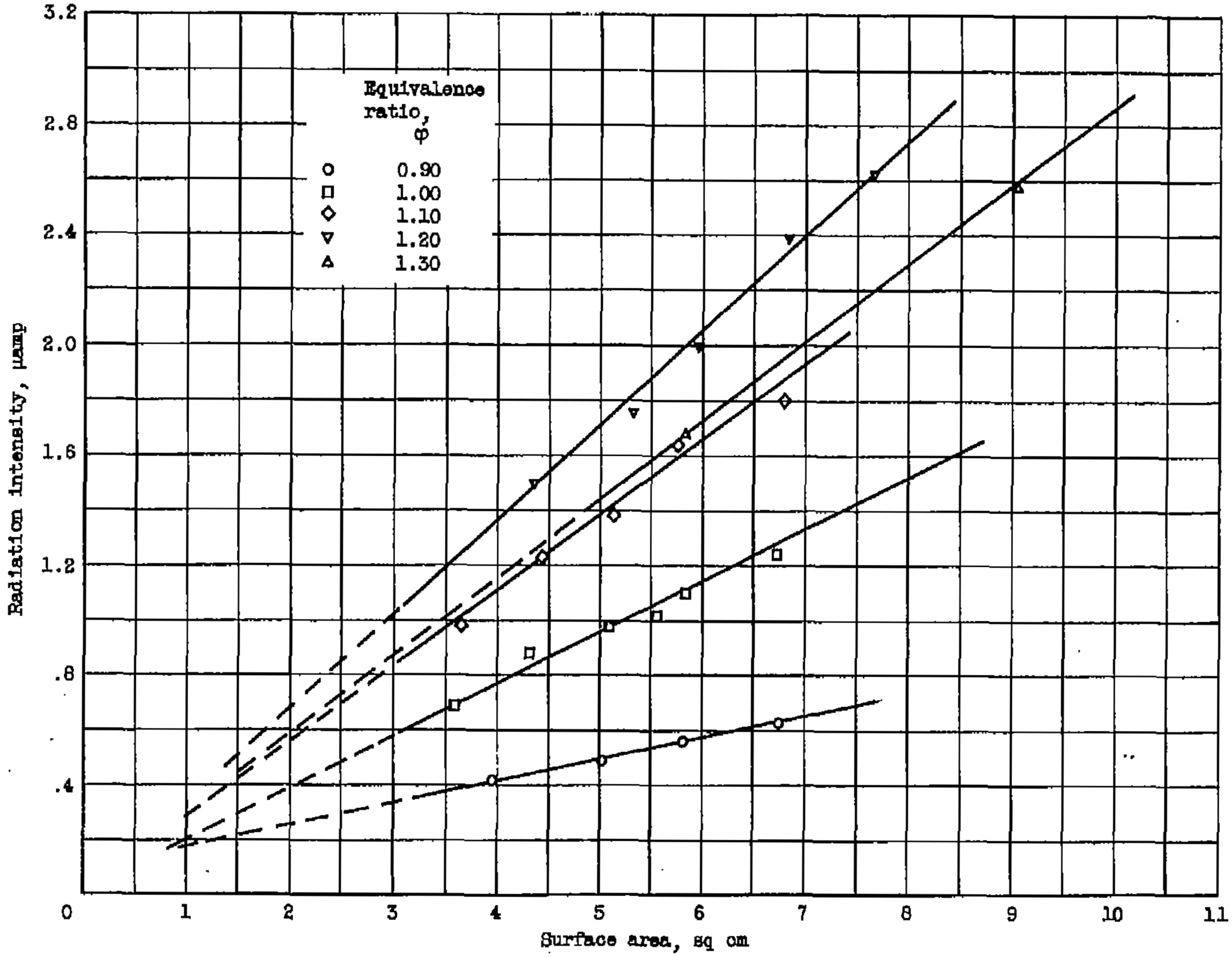
Figure 5. - Variation of laminar flame intensity with fuel flow. Burner diameter, 1.024 centimeters.

3276



(b) Blue filter.

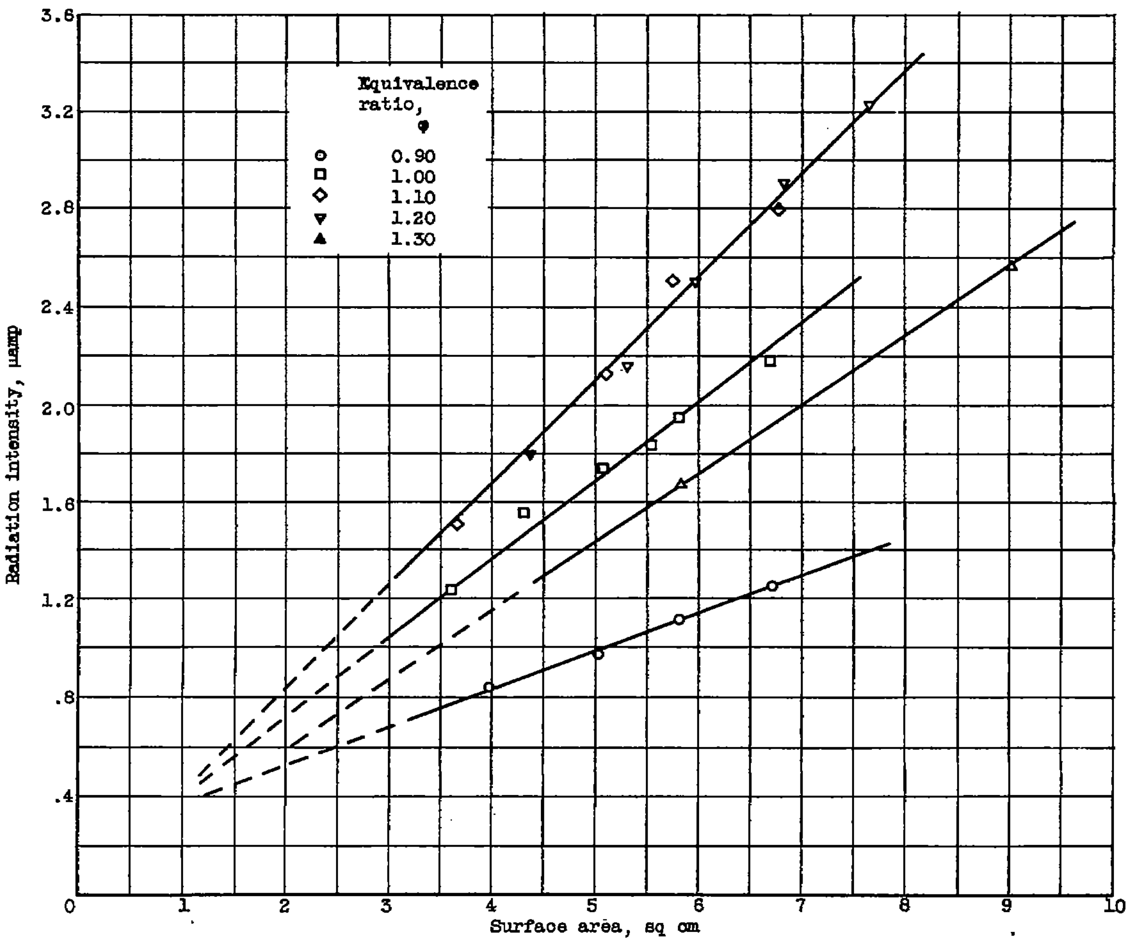
Figure 5. - Concluded. Variation of laminar flame intensity with fuel flow. Burner diameter, 1.024 centimeters.



(a) Yellow filter.

Figure 6. - Variation of laminar flame intensity with flame surface area. Burner diameter, 1.024 centimeters.

3276



(b) Blue filter.

Figure 6. - Concluded. Variation of laminar flame intensity with flame surface area. Burner diameter, 1.024 centimeters.

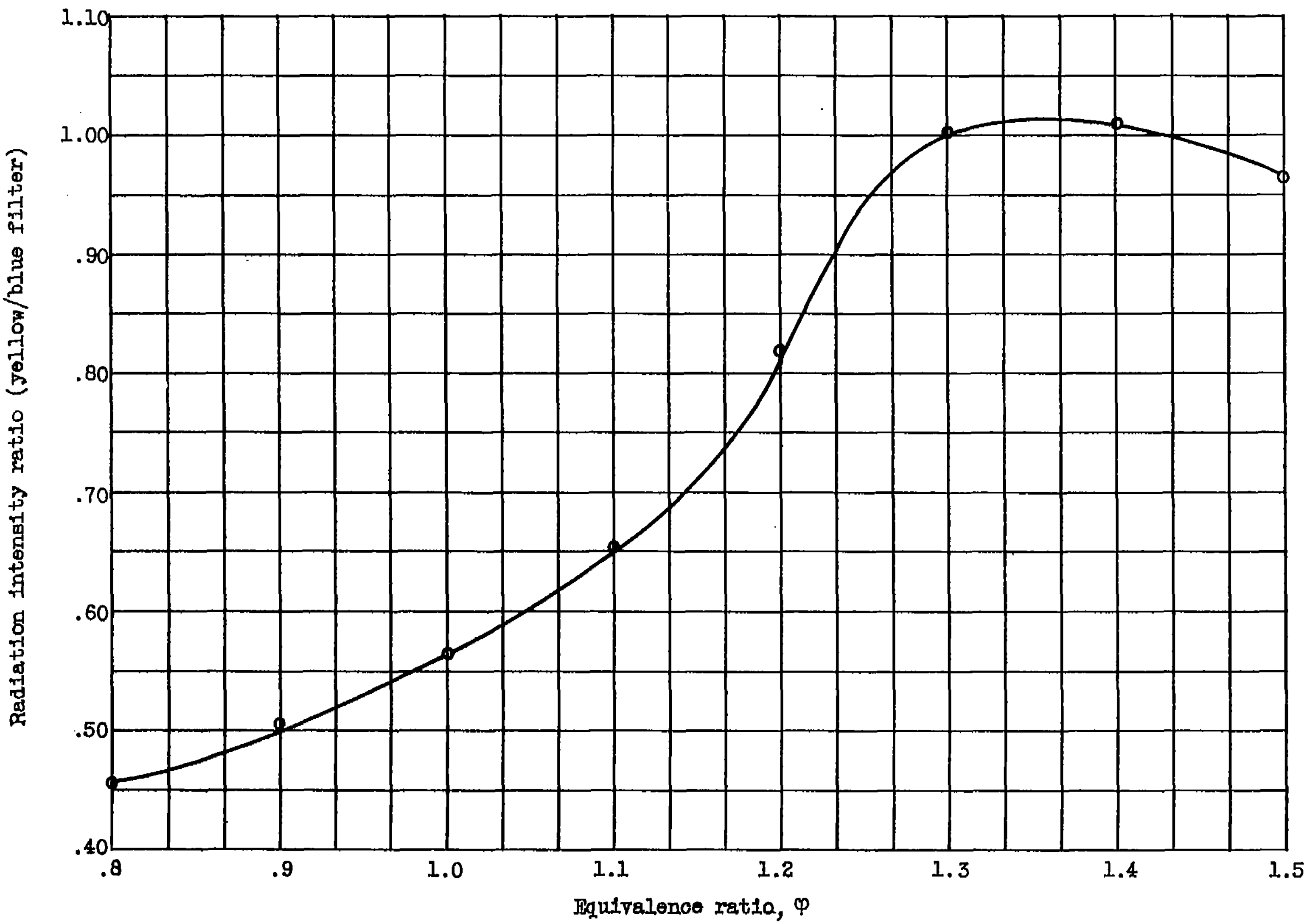


Figure 7. - Variation of laminar flame filter intensity ratio with equivalence ratio.

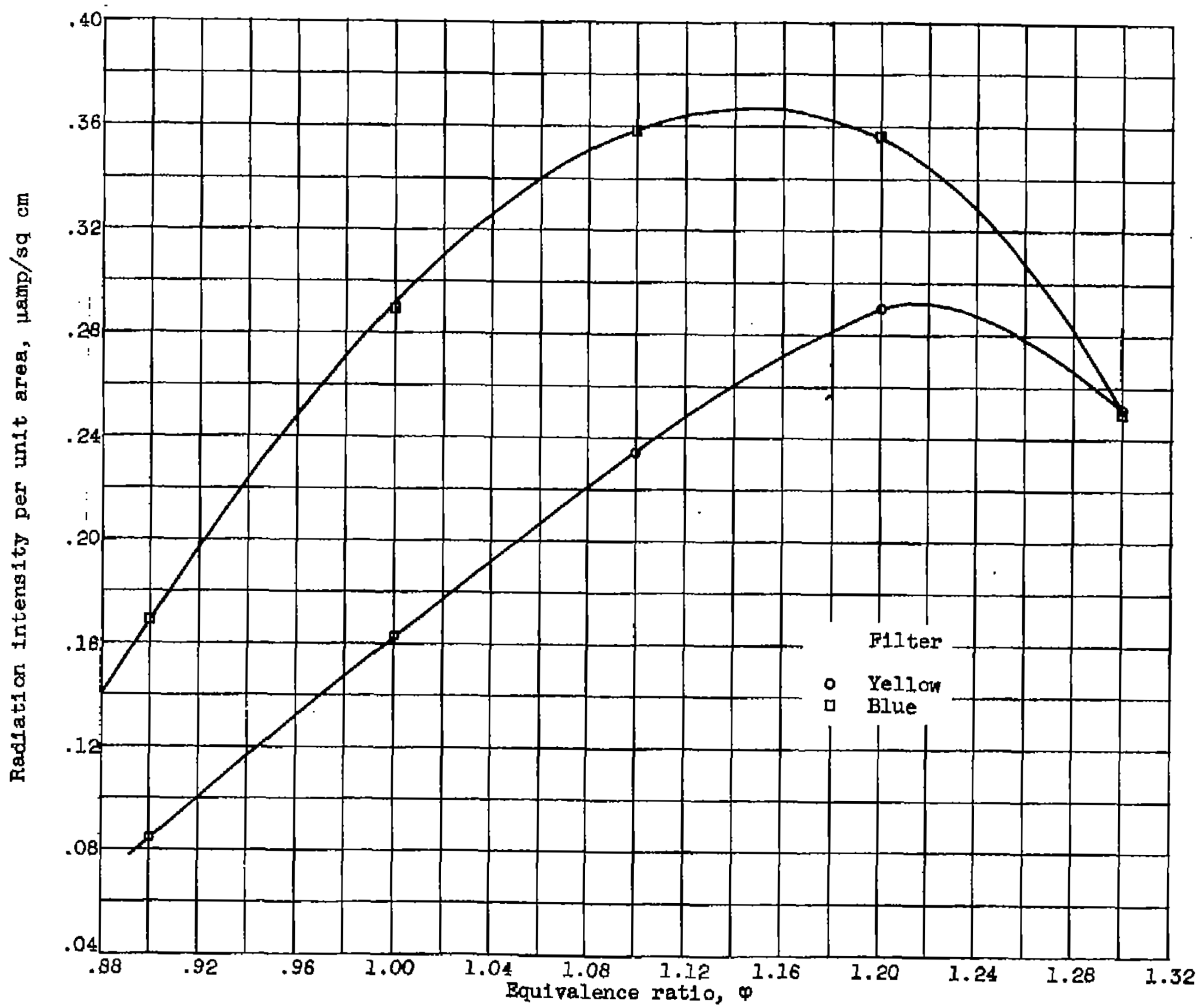


Figure 8. - Variation of laminar flame intensity per unit surface area with equivalence ratio. Intensities corrected to a burner diameter of 0.536 centimeter.

3276

CW-4 back

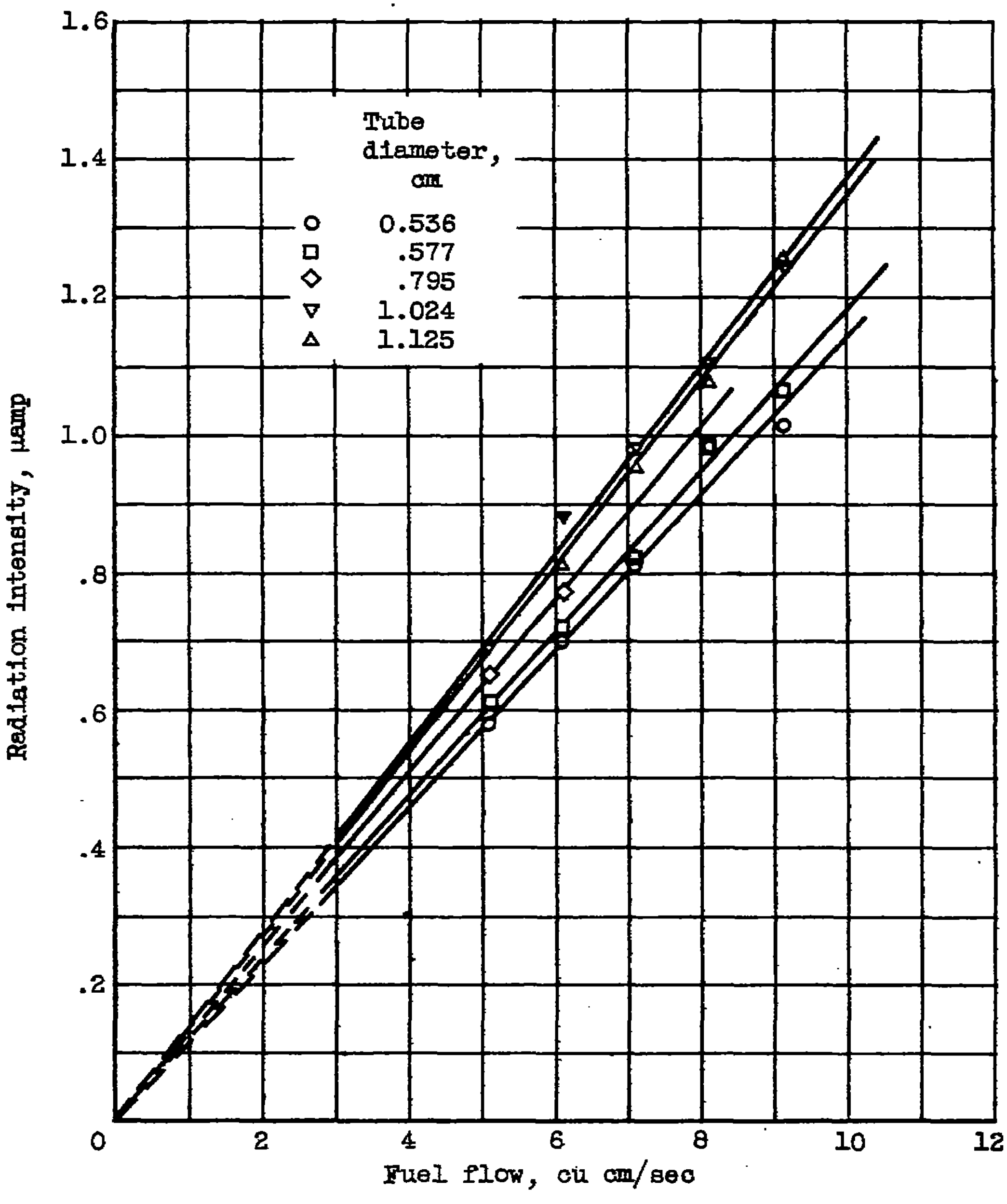


Figure 9. - Variation of laminar flame intensity with fuel flow for several burners. Equivalence ratio, 1.00; yellow filter.

3276

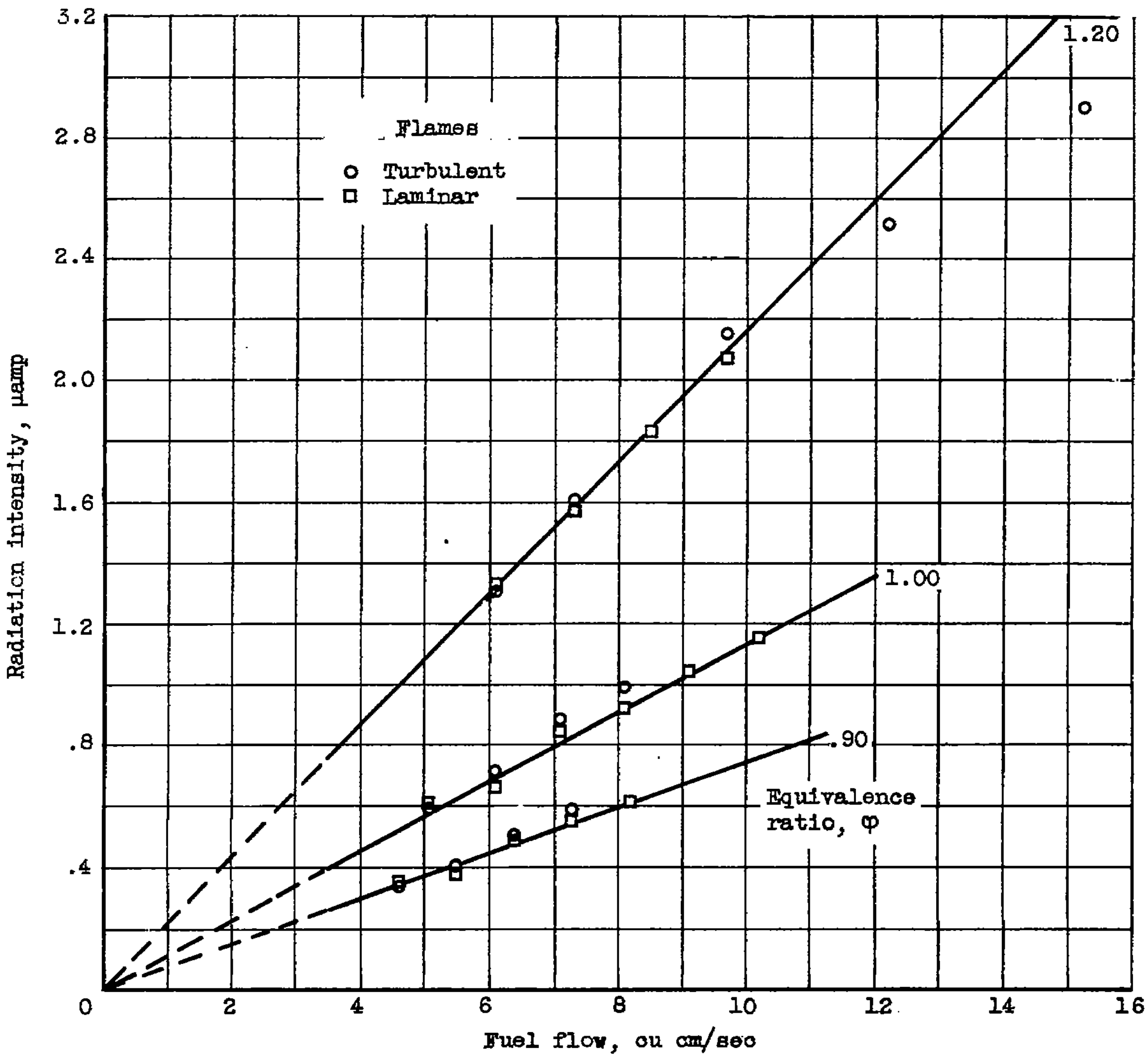
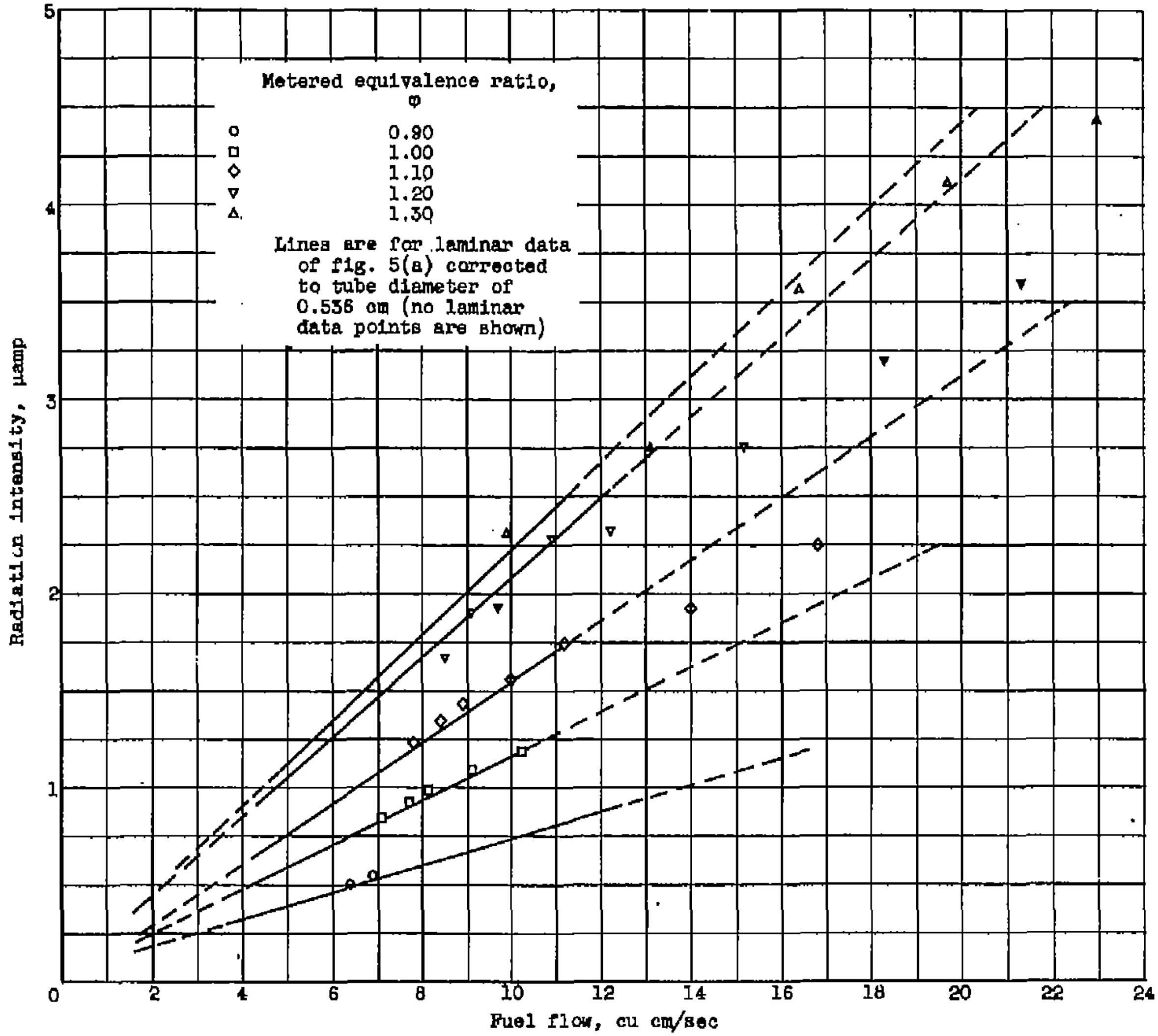
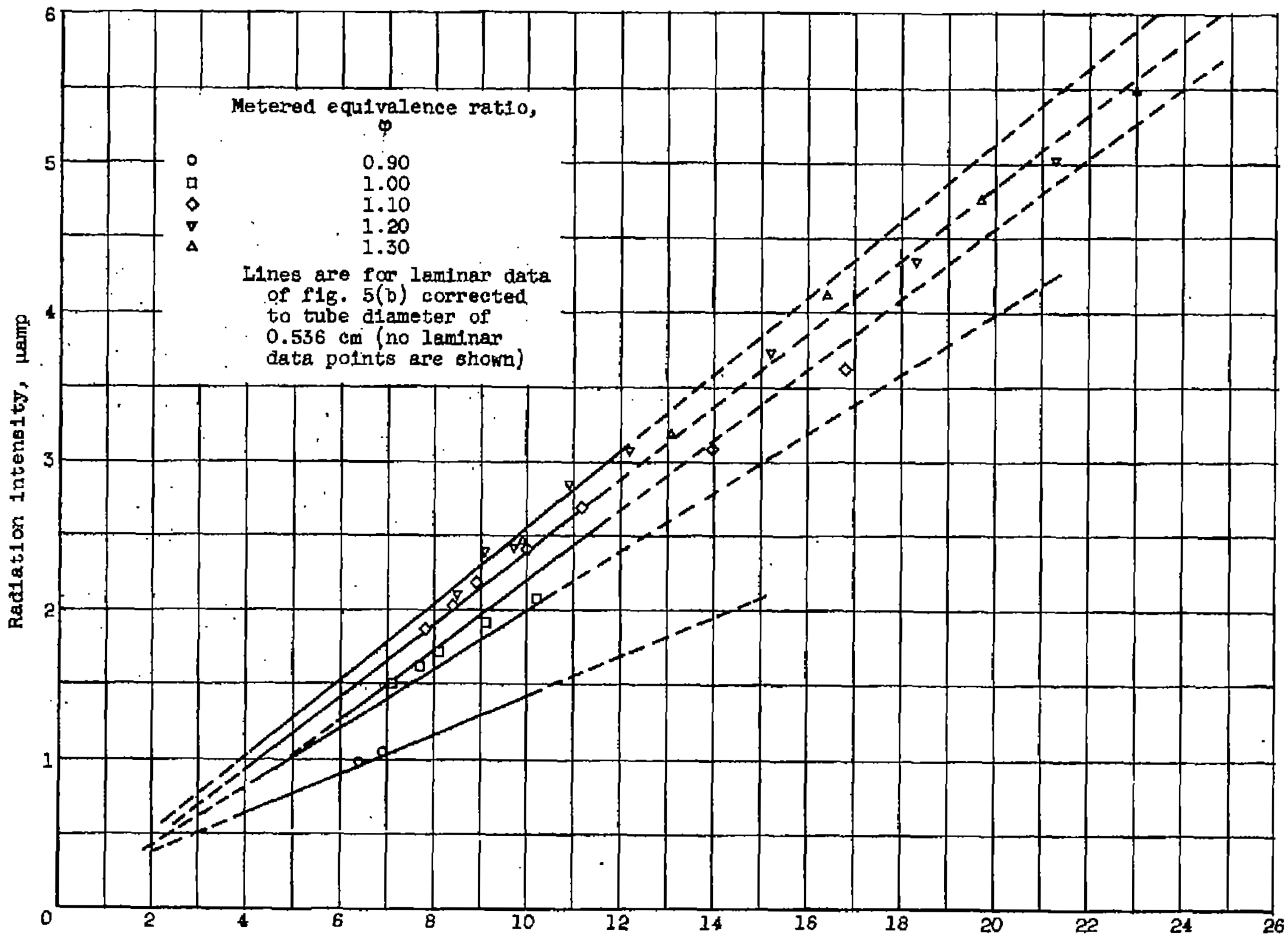


Figure 10. - Variation of laminar and turbulent flame intensities with fuel flow. Yellow filter; burner diameter, 0.536 centimeter.



(a) Yellow filter.

Figure 11. - Variation of turbulent flame intensity with fuel flow.



(b) Blue filter.

Figure 11. - Concluded. Variation of turbulent flame intensity with fuel flow.

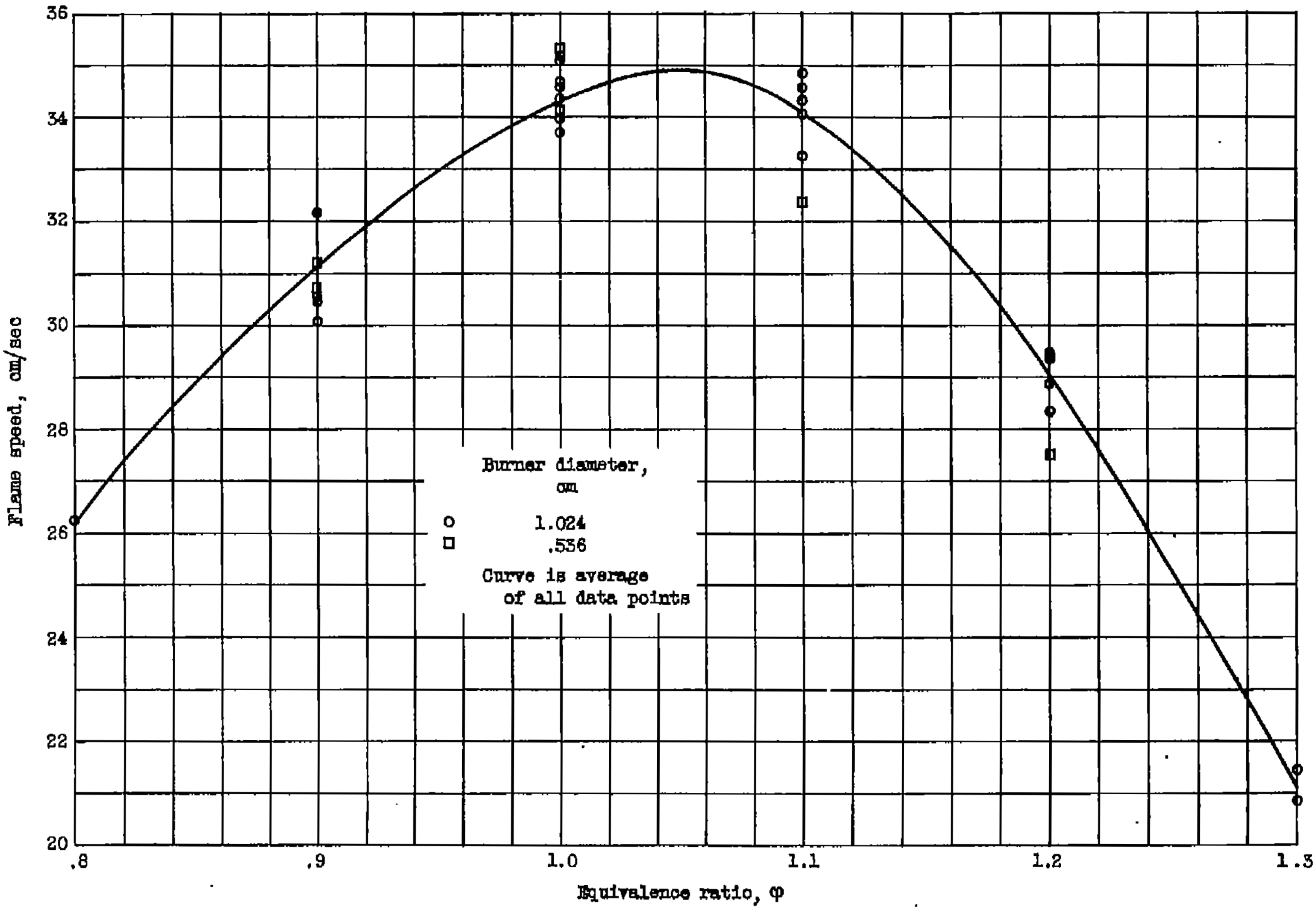


Figure 12. - Flame speeds of laminar propane-air flames.

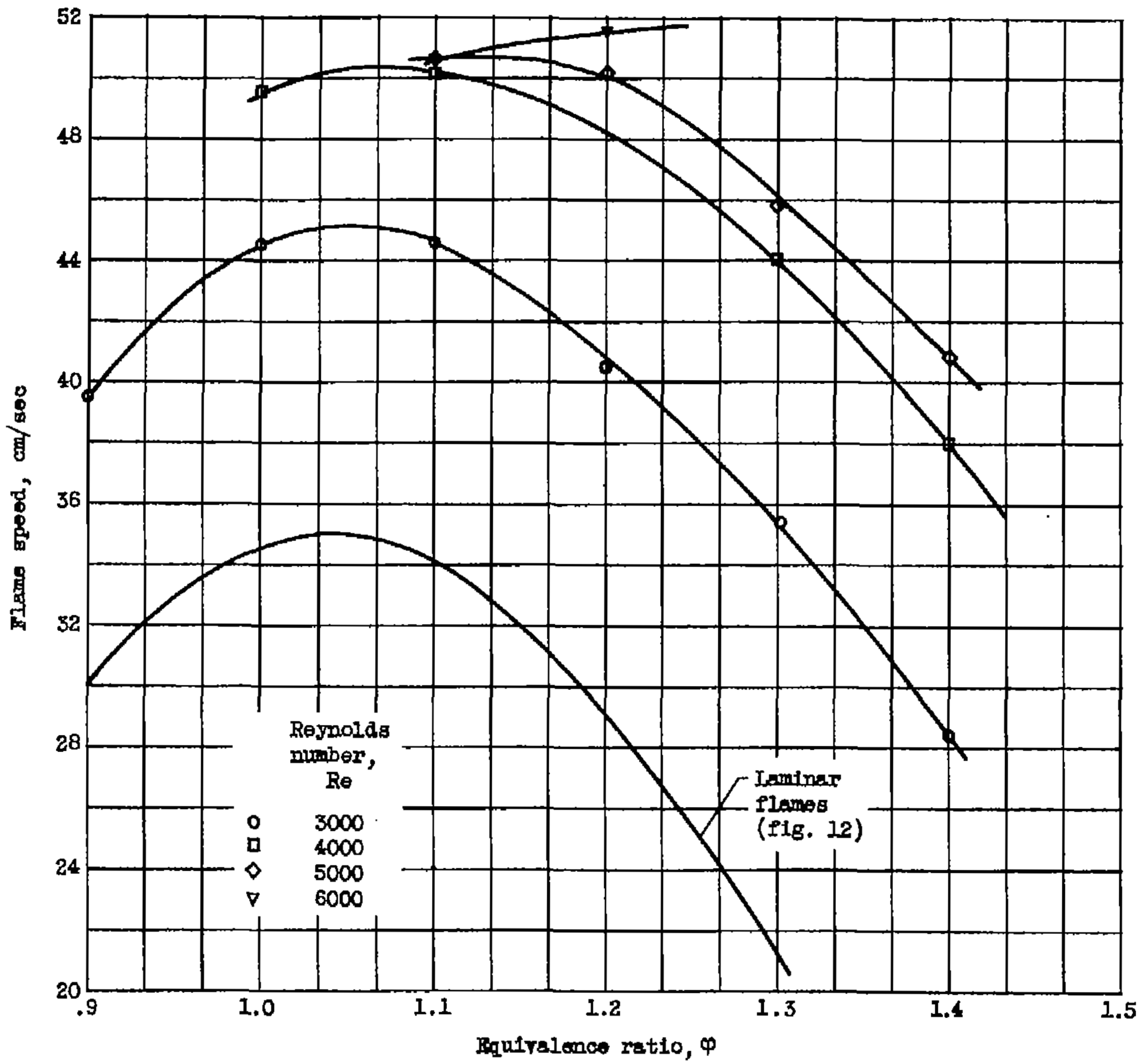


Figure 13. - Flame speeds of turbulent propane-air flames as measured by photographic method.

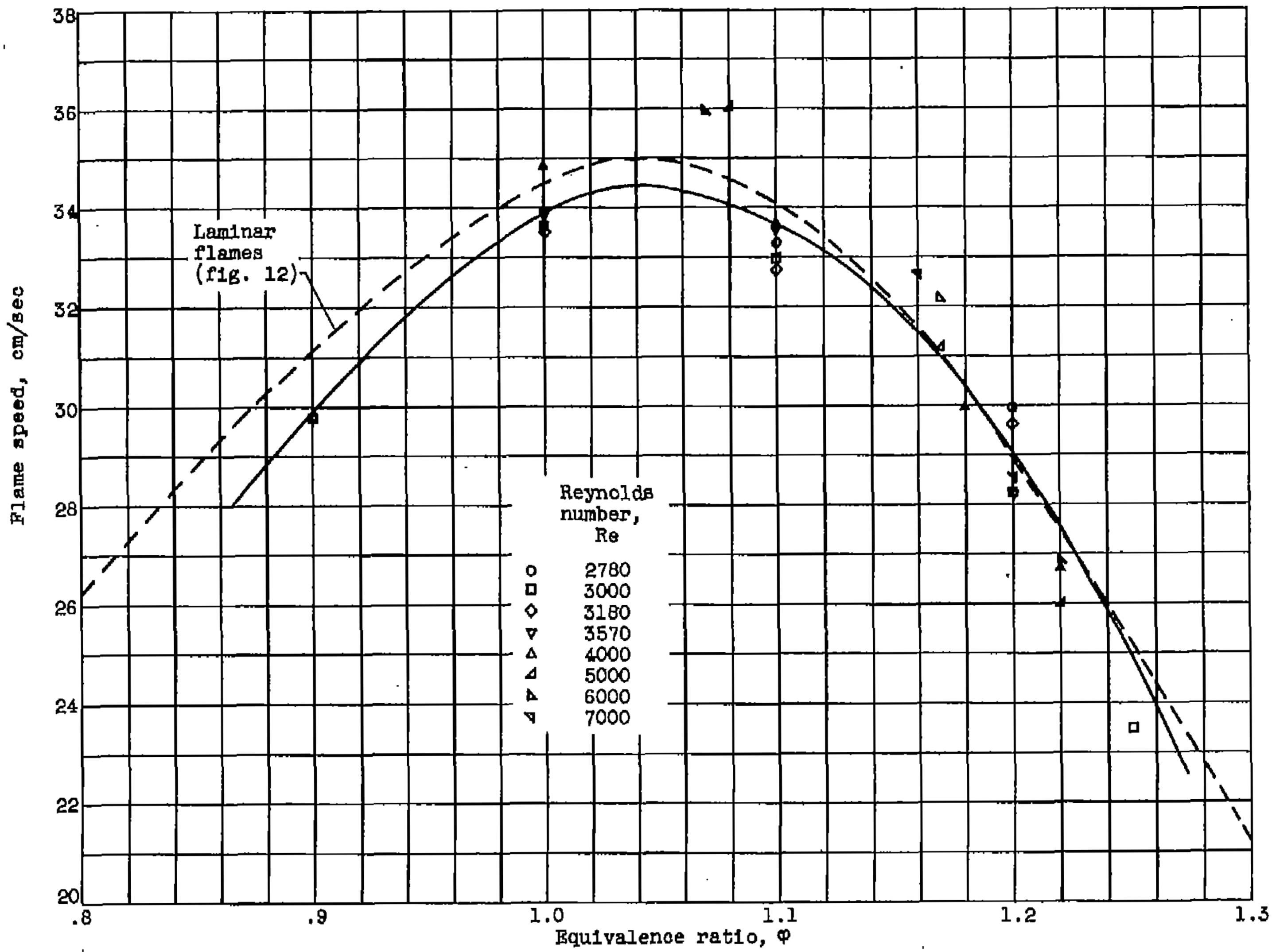


Figure 14. - Flame speeds of turbulent propane-air flames as measured by radiation method. Each point is average of measurements using blue and yellow filters.